Lobster Eye X-Ray Optics using Microchannel Plates

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ABSTRACT

We describe a novel system for focusing x-rays based on the eye of a lobster and a method for fabricating such optics using microchannel plates which have pores with square cross sections. Lobster eye optics will enable us to construct x-ray telescopes capable of simultaneously viewing a large fraction of the sky, making possible a new class of x-ray astronomy survey and monitoring missions. We have tested the x-ray optical properties of one of the first available square pore MCP's. We find that the angular resolution of the MCP lense is 5 arcminutes (FWHM). The resolution is limited by misalignment of the pore surfaces.

1 Introduction

Progress in X-ray astronomy has been tied very closely to advances in X-ray optics. X-ray astronomy was revolutionized by the flight of grazing incidence optics on Einstein. The large collecting area and high angular resolution available transformed X-ray astronomy into an essential branch of astrophysics. There is a growing perception of a need for large collecting area optics with modest angular resolution (and modest price tags) to provide the photons necessary for high resolution spectroscopy and for deep surveys. The current missions designed for large-area modest-resolution optics include the Broad Band X-Ray Telescope recently flown as part of the Astro mission on the space shuttle, the Soviet Spectrum-X-Gamma mission, the Italian X-ray astronomy satellite SAX, the Japanese X-ray spectroscopy satellite Astro-D, and the European high-throughput X-ray astronomy mission XMM. These missions will push the limits of the currently available techniques. It is crucial for future missions that new X-ray optics technologies are developed.

In this paper we describe a novel optical system, lobster eye optics, and a new technique for the fabrication of X-ray optics, utilization of the well known glass microchannel plate technology originally developed for electron multipliers. Application of microchannel plates (MCP's) to X-ray optical systems has the potential to provide a large optical surface area in a lightweight compact package at relatively low cost, greatly reducing the cost and weight of moderate angular resolution X-ray telescopes. Such reductions would allow important new X-ray astronomical observations to be made on low cost satellite missions and increase the effectiveness of larger missions.

The availability of MCP's makes possible the construction of a unique optical system based on the eye of a lobster. Lobster eye optics have never been constructed for X-rays due to the lack of a workable method of manufacture. This problem has been solved by recent developments in microchannel plate technology. Lobster eye optics are a radical departure from conventional X-ray telescopes in that they offer the possibility of constructing telescopes with unlimited fields of view; a lobster eye telescope could be constructed which would view the entire sky simultaneously. Such telescopes would enable the construction of an X-ray focusing all-sky monitor and provide a vast increase in efficiency for surveys of large areas of the sky relative to conventional X-ray optical systems.

In this paper, we will first review the characteristics of MCP's relevant to X-ray optics. We then describe lobster eye optical systems and their fabrication from MCP's. Following this, we show how lobster eye telescopes could help fulfill the objectives of NASA's next generation of x-ray astronomy payloads. Next, we describe the MCP optics research done at Columbia and present measurements of the pore alignment and surface roughness of a sample MCP. Finally, we consider what work must be done to develop MCP optics in the future.

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2 Microchannel Plate Optics

X-ray optics are intrinsically more difficult to fabricate than visible light optics because efficient X-ray reflection over a broad band occurs only at grazing incidence. The effective collecting area of a telescope is proportional to the projection of the area of the optical surface along the axis of incidence. A typical X-ray grazing angle of 1° implies that 60 cm^2 of optical surface is required for each square centimeter of effective area. Fitting a large surface area into the small volumes available in space experiments requires use of a large number of closely packed optical surfaces. The optical surfaces must reside on thin substrates, in order to pack them efficiently, and they must be accurately aligned.

Microchannel plates offer a means to manufacture large areas of closely packed surfaces. Microchannel plates are made by fusing together many glass fibers. Each fiber consists of a core glass and a sheath glass, similar to the optical fibers used in telecommunications. Rods of core glass are placed within cylinders of sheath glass to form a 'billet'. The billets are then drawn (they are pulled lengthwise so they lengthen and their diameter decreases) into fibers. Many such fibers are joined together to form a 'stack' which is then drawn again to form a 'boule'. The boules are then sliced and the core glass is etched away, leaving a pattern of channels in the sheath glass. The sheath glass with the channels is called a microchannel plate (MCP).

MCP's were originally developed as electron multipliers. In a conventional (electron multiplier) MCP, the rods of core glass are cylindrical, so the pores in the MCP are also cylindrical. While cylindrical pore MCP's were used in the first application of MCP's to x-ray focusing (Wilkins 1989), round pores are not suitable for efficient focusing optics. In a round pore the angle of reflection depends sensitively on precise location of the point of reflection; only a small fraction of the incident photons strike the correct region of the pore surface and are focused. With a square pore, any photon which has an odd number of reflections off each pair of orthogonal surfaces will be focused. This greatly increases the efficiency of focusing. It is possible to manufacture MCP's with square pores by starting with rods of core glass with square cross-section. At Columbia, we currently have samples of square pore MCP's from two manufactures.

The pitch (center to center spacing of the pores) of the MCP samples in our possession is on the order of 100 µm. This allows an order of magnitude closer nesting of optical surfaces than the current generation of X-ray telescopes. The frontal efficiency of the MCP's we have in hand is approximately 70%. Discussions with the manufactures indicate that this could be improved to 80% or 90%. This is significantly better than the frontal efficiencies of 10% to 40% for conventional X-ray optics. Assuming a cost of $2000 for a 40 mm diameter MCP having a frontal efficiency of 70% and a focusing efficiency of 25%, we find a cost of $1000 per square centimeter of effective area. This compares favorably with the typical cost of $10,000 per square centimeter of effective area for conventional X-ray optics, (Gorenstein 1979). Scaling from measurements of a sample square pore MCP, which has a pore width of 60 µm and a length to width ratio of 80:1, the same MCP would have a total mass of 14 grams giving a mass of 7 grams of glass per square centimeter of effective area. If the support structure is carefully manufactured, perhaps using a carbon-fiber epoxy-resin composite, the complete optical system could have a mass per square centimeter of effective area only a few times this. Thus MCP's offer the possibility of extremely low mass optics.

In the remainder of this section, we first describe a novel optical system, lobster eye optics, which can be fabricated efficiently with MCP's. MCP lobster eye optics make possible the design of telescopes which are qualitatively different from any existing X-ray optics. The main new feature is the possibility of extremely large fields of view. Following that, we give brief descriptions of two lobster eye x-ray telescopes to suggest how the optics could be used on future x-ray astronomy missions. Then we describe how MCP's could be used in more conventional optical systems.

2.1 Lobster Eye Optics

The bulk fabrication of square pores makes possible the fabrication of an, as yet unrealized, X-ray optical system which offers the promise of very large fields of view. These optics are based on the eyes of macruran crustaceans, *i.e.* lobsters (Land 1978). Their application to X-ray astronomy was first described by Angel (1979). A lobster eye consists of a large number of small tubes with square cross section. The inner walls of the tube are reflective and the central axis of each tube points toward a common center of curvature. A cross-section of a lobster eye is shown in figure 2.1. Parallel light rays striking the eye are reflected to a curved focal plane halfway between the lense and the center of curvature. The focal length is half the radius of curvature. The lense is suitable as an X-ray telescope because it employs reflections near grazing incidence. A significant advantage of the lense is that it has no optical axis.

Therefore, there is no limitation on the field of view. This makes lobster eye optics ideally suited for survey and monitoring missions.

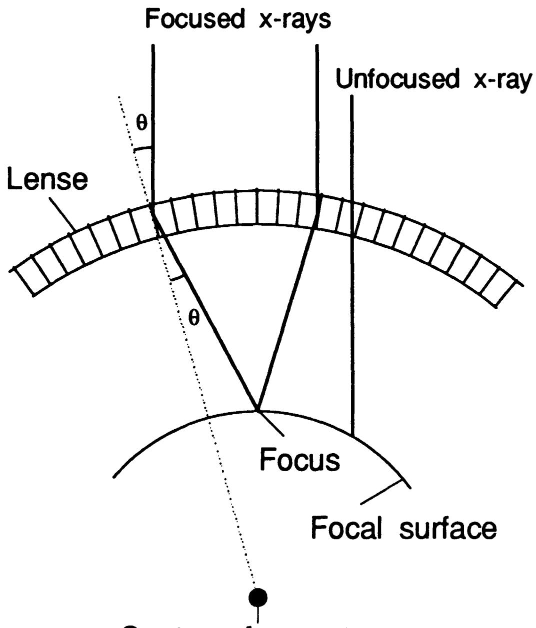

Figure 2.1: Cross-section of a lobster eye. Parallel light-rays are focused by the spherically curved lense onto a spherical focal surface. All the reflecting surfaces point towards a common center of curvature.

The angular resolution of the lense is limited by spherical aberration, the finite spacing between reflectors, and diffraction. The spherical aberration depends on the range of allowed reflection angles of X-rays. The probability that a given X-ray will reflect off a surface depends on the X-ray energy, the angle of incidence between the X-ray and the surface, and the material composition of the surface. There is a maximum angle of incidence, called the critical angle or θ_c, above which the reflectivity drops rapidly to zero. This places a limit on the maximum allowed reflection angle. The degradation of image quality due to spherical aberration is $\Delta\theta = 0.124 \cdot \theta_c^3$, where $\Delta\theta$ is the angular resolution. For gold, the aberration is less than 1 arcmin for energies above 0.6 keV, (critical angles less than 0.13 radians). For very small pore sizes, diffraction will affect the angular resolution according to $\Delta\theta = \lambda/w$. Selection of pore sizes greater than 25μm will limit diffraction broadening to less than 10 arcsec for energies greater than 1 keV.

For our choice of energy range (> 1 keV) and pore size (> 25 μm), the characteristics of the image are determined mainly by the geometrical optics of the lense. The image has a triangular cross-section with a size given by $\Delta\theta = 2\varepsilon$, where $\varepsilon = w/r$ is the angle between two reflectors viewed from the center of curvature. To achieve an angular resolution of 1 arcmin with a focal length of 1 m, the reflectors must be nested with a spacing of 300 μm. A lense of this type with a reflector spacing of significantly less than 300 μm can be constructed using MCP's.

The image produced by a lobster eye has four components: a point focus, two line foci, and an unfocused background. The size of the point focus is given by the angular resolution of the lense, $\Delta\theta_f = 2\varepsilon$. The size of the unfocused component is limited because the pores act as collimators. The angular size is given by the ratio of pore width to pore length, $\Delta\theta_u = w/l$. The line foci have a narrow dimension equal to $\Delta\theta_f$ and a long dimension equal to $\Delta\theta_u$.

The four image components are caused by X-rays which reflect differing numbers of times in the square pores. As shown in figure 2.1, an X-ray which undergoes a single reflection will be focused in one dimension. Unreflected X-rays are not focused. Because the angles of incidence and reflection are maintained for multiple reflections, an X-ray reflected several times between two parallel plates is either focused, if the number of reflections is odd, or unfocused, if the number of reflections is even. In two dimensions the number of possibilities is squared: the X-ray can be focused or not in each dimension. This gives rise to: the point focus, for X-rays which have an odd number of reflections in both dimensions; the line foci, for X-rays which have an odd number of reflections in one dimension and an even number of reflections in the other; and the unfocused background, for X-rays which have an even number of reflections in both dimensions. The line foci and the unfocused X-rays add to the background and decrease the sensitivity. Proper treatment of the line images also significantly complicates the image analysis. However, since the line images are formed by single reflections they add considerable effective area at high energies where the reflectivity is low.

2.2 All Sky X-Ray Monitor

Lobster eye optics have no intrinsic limitation on their field of view. This naturally suggests that the optics be used for an all sky monitor. Such a monitor

could be used to detect transient phenomena (including X-ray bursters, soft gamma repeaters, and X-ray flares) and to study the time variability of large numbers of objects on many time scales. Continuous monitoring of a large fraction of the sky would be invaluable in measuring the intensity and duration distributions of the various classes of transients and determining the nature of the objects responsible. Many continuously emitting sources have complex time variations, examples include cataclysmic variables, high-mass and low-mass X-ray binaries, and active galactic nuclei. The temporal progression of the spectral and intensity states of these sources would be best studied by continuous monitoring over extended periods. Such monitoring would certainly deepen our understanding of these objects.

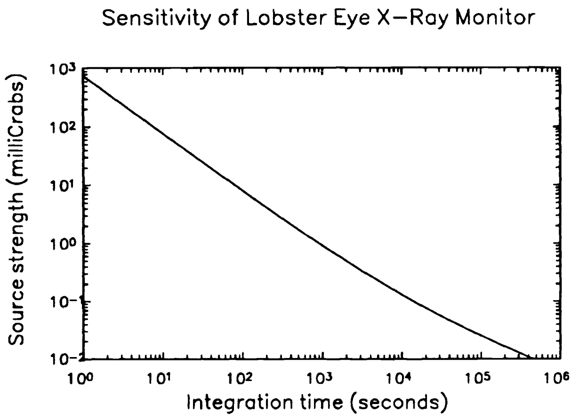

Figure 2.2: Sensitivity versus integration time of the lobster eye half-sky monitor for sources with a Crab-like spectrum.

To illustrate the potential of the optics, we will outline the design of an instrument which could be flown on a moderate sized mission. The main element of the satellite is a spherical lobster eye lense, with a radius of 75 cm, coupled to a spherical detector. The field of view of the lense-detector assembly would be as close to 4π steradians as possible within the constraints of the mission. The monitor is likely to be constructed as a mosaic of smaller lense-detector assemblies, perhaps 60 units each with a field of view of 30° by 30°. Such an assembly would ease the engineering requirements on the lense and detector and vastly increase the redundancy of the system. Large-format curved-MCP x-ray detectors suitable for such a system have been developed successfully for the Alexis mission (Siegmund *et al.* 1990).

An angular resolution of 1 arcmin should be adequate for the monitor. Higher resolution would not significantly increase the science of the mission, and would vastly increase the complexity of the required detectors. If we choose a lense pore size of 60 μm then the geometric resolution limit, for a focal length of 37.5 cm, will be 0.6 arcmin. The diffraction limit will be less than this for wavelengths shorter than 100 Å. Since the focal length of the system must be restricted to fit into the available payload volume, the high energy response of the optics will be limited. To optimize the design for the maximum point focused energy in the band 0.5 to 2.5 keV, we have selected a pore length to width ratio of 50:1.

To calculate the sensitivity of the instrument we have assumed a uniform detector quantum efficiency of 60% between 0.2 and 2.4 keV. We considered only the point focus of the lobster eye; use of the partially focused arms of the image would improve the sensitivity. We used reflectivities calculated for gold. The background has components due to diffuse cosmic x-rays and due to local sources (the detector background). For the detector background, we used that measured by the Rosat HRI (Zombeck 1990). This background is about twice that expected from the diffuse x-rays (Wu *et al.* 1990). The limiting sensitivity, which we define as the minimum source strength which will produce ten counts above a four sigma fluctuation in the background, as a function of observing time for sources with a Crab-like spectrum is shown in figure 2.2. The minimum detectable source strength for a ten second integration is 75 milliCrabs. The sensitivity for a 1000 second observation is 0.9 milliCrabs. The lobster eye offers a significant increase in sensitivity over non-focusing monitors, like pin-hole cameras or coded aperture masks, due to the background reduction provided by focusing.

2.3 Wide Field X-Ray Telescope

The X-Ray Schmidt Telescope, part of the AstroTech 21 mission set, is planned as a wide field, moderate angular resolution instrument to complement the narrow field, high angular resolution telescope aboard AXAF. The goal for the satellite is to perform a rather deep survey over a large fraction of the sky, (a few thousand square degrees). One of the main science objectives of such a survey will be study of the large scale structure of the universe. Recent (optical) surveys have shown the existence of structures on scales as large as the depth of the survey. Inhomogeneities on such scales are very difficult to reconcile with the lack of

fluctuations in the microwave background found by the Cosmic Background Explorer (Mather *et al.* 1990). An x-ray survey of clusters of galaxies over a contiguous region of a few thousand square degrees of sky would provide key insights to the formation of the large scale structure, particularly if the observations are sensitive up to 7 keV (Sarazin 1988).

The main advantage of a lobster eye telescope in performing large surveys is its large field of view. The efficiency of a telescope for surveys is the product of the effective area and the field of view. The fields of view of conventional X-ray telescope designs are limited to one or two square degrees. The field of view of a lobster eye telescope is limited only by the size and weight available on the spacecraft. A lobster eye telescope with a 2 meter focal length could easily have a 200 square degree field of view and be sufficiently compact for launch as a moderate sized mission. The primary factor limiting the effectiveness of the lobster telescope for surveys will be the angular resolution. To allow the best possible sensitivity without source confusion, it will be crucial to improve the angular resolution of the optics to sub-arcminute levels.

We find that a lobster eye telescope with a focal length of 2 meters optimized for response near 7 keV will have an effective area of 12 cm^2 for the point focus and 26 cm^2 for all (point and line) focused X-rays at 7 keV. At 1 keV, the same telescope will have an effective area of 27 cm^2 for the point focus and 92 cm^2 for all focused X-rays. This is substantially less than for a Wolter telescope of the same focal length. However, for survey work the vast increase in field of view more than compensates for the reduced effective area. If we calculate the product of point focus effective area times field of view for the lobster eye telescope we find 2400 $cm^2 \cdot degree^2$ at 7 keV and 5400 $cm^2 \cdot degree^2$ at 1 keV. This is an order of magnitude improvement in survey efficiency compared with a Wolter telescope designed for a survey mission (Burg, Burrows, and Giacconi 1990).

2.4 KirkPatrick-Baez Optics

Square pore MCP's can also be employed in the construction of more conventional optical systems, particularly KirkPatrick-Baez telescopes. KirkPatrick-Baez optics are typically made using flat plates which are curved in one dimension. The plates typically extend several centimeters along the optical axis, so that curvature is necessary to maintain good angular resolution. Because the optical surfaces ('flat plates') in MCP's are packed so closely, their length along the optical axis is a few millimeters or less. Therefore, a flat approximation to a KirkPatrick-Baez telescope made using MCP's can still maintain moderate angular resolution. The limitations on the angular resolution of the flat plate KirkPatrick-Baez telescope are essentially the same as those discussed for lobster eye optics in section 2.1.

KirkPatrick-Baez optics offer a significant advantage in manufacture over lobster eyes in that they require the MCP's be curved only in one direction. This makes it significantly easier to bend the MCP without distorting it.

3 Optical Measurements

The main requirements for the production of efficient optical systems from MCP's concern the geometry of the pore surfaces. First, the pore surfaces must be aligned sufficiently accurately to produce the desired image quality. Second, the pore surfaces must be smooth (have low microroughness) in order to reflect x-rays efficiently. In this section, we present measurements of the surface roughness and geometric alignment of first available square pore MCP's.

3.1 Focusing with a Flat MCP

The first crucial question in the production of MCP X-ray optics concerns the geometric alignment of the pores. The accuracy with which the pores are aligned is likely to be the dominant factor which determines the angular resolution of telescopes constructed from MCP's.

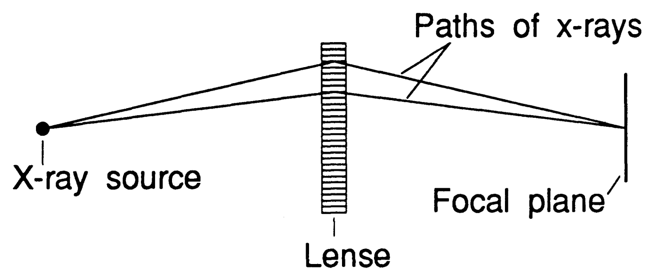

Figure 3.1-a: Point to point focusing with a flat MCP lense. X-rays are produced by a point source and then reflected to a point focus.

We have constructed an apparatus to test the basic properties of focusing by square pore MCP's using flat MCP's. The MCP is used to focus diverging x-rays from a point source to an image. The geometry of the apparatus, shown in figure 3.1-a, is essentially identical to that used by Wilkins (1989). Diverging x-rays are

produced by a point source. The diverging rays strike the MCP. Snell's law implies that the incident and reflected angles are the same, therefore the MCP focuses the diverging x-rays to a point, as shown in the figure. The source-lense distance and the image-lense distance are both 1.64 m. The photons are detected at the focal plane by an imaging proportional counter.

The MCP was rotated so that the pore surfaces were aligned with the x and y-axes. This alignment was done using the diffraction pattern produced with optical light. The MCP was tilted so that the pore central axes were (approximately) parallel with the z-axis. A magnesium anode was used in the x-ray tube, producing 1.25 keV x-rays. The anode spot size (the size of the 'point' source) was 0.8 mm in diameter. The proportional counter was filled with P20 (80% Argon - 20% Methane) at 1 atmosphere. The position resolution of the detector was measured to be 1.2 mm. The absorption depth for Mg K-α x-rays in Argon at 0.8 atm is less than 5 mm, so image smearing due to finite focal plane depth is negligible.

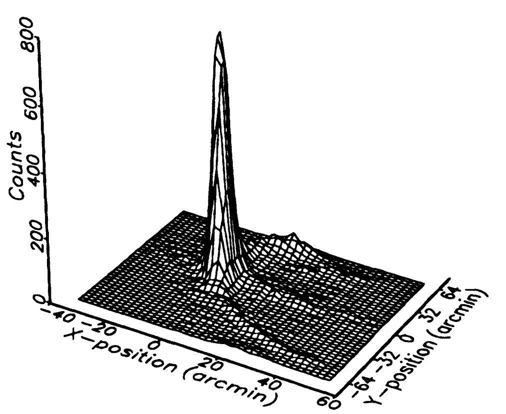

Figure 3.1-b: X-ray image formed using a square pore MCP. The plot is a histogram of counts versus position on the focal plane. The coordinates are given as angular distance from the optical axis. The width of the image in the focused dimension (x-axis) is 6.3 arcmin FWHM.

For the measurements described below, a collimator was placed just in front of the MCP. The collimator was an aluminium plate with a 1 mm diameter hole positioned 34.5 mm from the beam axis, so the nominal grazing angle for x-rays incident on the MCP is 1.2°. The collimator was displaced from the beam axis along the x-axis, but not along the y-axis. Therefore, the x-rays forming the image must undergo an odd number of reflections in x, but need not be reflected in y. The extent of the image in the x-direction is determined primarily by the alignment of the pore surfaces; the width of the cross section of the image along the x-axis (essentially the point spread function) indicates the angular resolution achievable with the MCP.

An image produced by this apparatus is shown in figure 3.1-b. The plot is a histogram of the number of photons detected versus position in the focal plane. Most of the photons (3/4) are concentrated in the central peak. The remainder are distributed in three arms. The width along the x-axis of the central peak of the image in the figure is 6.3 arcmin (FWHM). After removing the contributions due to the finite size of the x-ray source and the position resolution of the detector, we find that the image width due to pore misalignments in the MCP is 4.9 arcmin. We have made a number of images by illuminating different 1 mm^2 areas of the MCP surface. The image width remains roughly constant across the MCP. Therefore, the quality of the relative alignment of local groups of pores is roughly the same across the MCP. The distribution of image widths has a mean of 5.0 arcmin and a FWHM of 0.5 arcmin. Since the change in the angle of the reflected x-ray is twice the change in the angle of the reflecting surface, this implies that pores separated by less than 1 mm are aligned to an accuracy of 2.5 arcmin.

To investigate the alignment of pores over larger areas of the MCP, we moved the MCP while keeping the collimator and the rest of the apparatus fixed. Figure 3.1-c shows a plot of the centroid of the image versus the position of the MCP. The centroid of the image shifts as we scan across the MCP. This means that the average alignment of pores varies as a function of position on the MCP. Pore alignment over distances scales larger than a few millimeters is significantly worse than the alignment on scales less than a millimeter.

The MCP used for these tests was constructed, by Galileo Electro-Optics, primarily to demonstrate that square pore MCP's could be manufactured. It was fabricated using the block press method of MCP manufacture. It is believed that this method has limitations

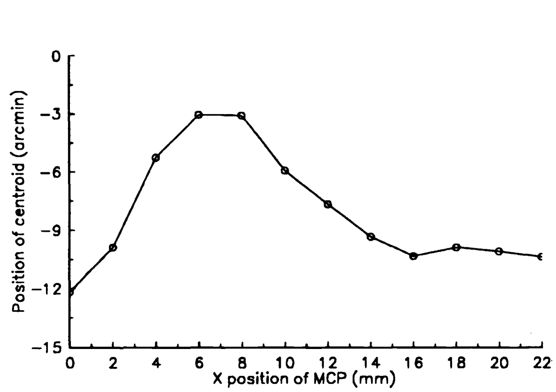

Figure 3.1-c: Image centroid versus position of MCP. The MCP was moved along the x-axis, keeping the collimator fixed. The motion of the image centroid is due to global variations in the pore alignment.

if a high degree of square pore alignment is desired. A second generation of square pore MCP's is currently being built using improved techniques for stacking the fibers and a procedure for drawing the glass which should decrease distortions of the core glass and therefore of the pore geometry. We anticipate that several iterations of manufacture and measurement will be necessary as MCP manufacturers improve their techniques to meet our goals. According to discussions with MCP manufactures, an alignment accuracy of 30 arcsec should be achievable with refinements to the current manufacturing procedures.

Another problem related to the pore geometry arises because lobster eye telescopes require that the pore surfaces point to a common center of curvature, while MCP's are typically produced with all the pore surfaces parallel. To construct lobster eye optics it will be necessary to change the alignment of the pore surfaces. It is possible to alter the shape of an MCP, and therefore the alignment of its pores, in a controlled and permanent way by deforming the MCP while heating it, this process is called 'slumping'. It is important to note that the slumping must not disturb the pore alignment. We note that KirkPatrick-Baez optics can be constructed with MCP's which are curved in only one dimension. It should be significantly easier to maintain the pore alignment under cylindrical curvature.

3.2 Surface Roughness of Pores

The second crucial question in the production of MCP X-ray optics is the quality of the pore surface. Roughness of a reflective surface causes scattering and a decrease in reflectivity of the surface. It has been found that average surface roughness is sufficient to characterize the degradation of X-ray efficiency due to surface errors with length scales shorter than approximately 1 mm, (Beckmann and Spizzichino 1963). The attenuation in image intensity is given by the Strehl factor. Assuming two orthogonal reflections, the Strehl factor is equal to $\exp[-(4\pi\sigma \sin\alpha/\lambda)^2]$, where σ is the average (RMS) surface roughness, α is the grazing angle, and λ is the X-ray wavelength. To retain 50% of 6 keV X-rays at the critical grazing angle of 0.7° would require a surface roughness of 10Å.

We have obtained measurements of the microroughness of a square pore MCP fragment using an optical profiler. The measurement was done for us by the WYKO Corporation. The MCP used was an engineering sample fragment from Philips with a pore cross-section of 85 µm by 85 µm and a wall thickness of 15 µm. It was prepared by cutting it into small pieces, a few millimeters on each side, and then shearing each piece to make the exposed surfaces parallel to the pore axes. Several regions, each 102 µm by 102 µm, were selected for measurement. The areas containing remnants of pore walls perpendicular to the pore surface of interest were masked out before the analysis. It was found that the pore surface has a roughly cylindrical curvature with a sagitta of 950 nm over the 85 µm pore width. This curvature is most likely due to small-scale nonuniformities in the chemical etching process used to remove the core glass. The curvature must be limited to a sagitta of 200 nm to prevent smearing of the image. After the cylindrical curvature was subtracted out, the RMS roughness of the pore surface was found to be 180 Å. This value was constant (within 10%) over all of the regions measured.

Several steps in the manufacture of MCP's roughen the pore surface. As mentioned above, pores are formed in sheath glass of MCP's by etching out the core glass. The etching process tends to score and pit the glass surface, creating microroughness. Also, diffusion of the two different glasses across their boundary gives rise to irregularities in the surface layer which are revealed when the core glass is removed.

To achieve the high quality surface finish needed for efficient x-ray optics, it will be necessary to develop techniques to either produce MCP's with smoother pore surfaces or to smooth the surfaces after the pores have been etched. While we intend to investigate ways to minimize the roughening caused by these processes, we plan to concentrate primarily on developing techniques to reduce the surface roughness after manufacture. We are currently investigating chemical polishing and re-annealing. We have tentatively rejected lacquer coating because the thickness of the lacquer coat required is a fair fraction of the MCP pore thickness and due to the difficulty of coating very small pores with a high viscosity fluid.

4 Conclusions

Recent developments in the manufacture of microchannel plates offer an effective means to produce x-rays optics via the use of square pore MCP's. Using the first available samples of square pores MCP's, we have tested some of their basic optical properties, including the alignment of pores over short and long distance scales and the microroughness of the pore surface. The pore alignment on short distances scales was measured to be 5 arcmin. Considering the early stage of square pore MCP development, this is encouragingly close to our initial goal of 1 arcmin. However, measurements on larger scales show significant distortions in the MCP. Improvements in MCP manufacturing techniques will be required to improve the pore geometry. Our measurement of the pore surface roughness has shown, as expected, that it is much worse than is acceptable for efficient x-ray optics. Techniques to polish the surface must be developed.

MCP optics offer the possibility of large area optics with low mass and relatively low cost. While MCP's can be employed in conventional optical systems, they make possible the manufacture of a novel optical system based on the eye of a lobster. Lobster eye optics offer a qualitatively new capability for observing the x-ray sky: very large field of view focusing telescopes. If successfully developed, these optics could greatly increase the efficiency of future x-ray survey and monitoring missions.

5 Acknowledgements

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